Increased Performance, PCM112 Integration and Mechanical Sound Reduction of the WRACE 674

Blake Bomkamp, Brandon Riehle, Matthew Massman
Glenn R. Bower, Ethan K. Brodsky
University of Wisconsin – Madison

Abstract

For the 2019 Clean Snowmobile Challenge the University of Wisconsin has engineered a new and improved version of the WRACE 674. The 2015 Ski-Doo MXZ Sport chassis is powered by a Rotax ACE four-stroke engine, which is bored and stroked to 674cc. The 2019 entry features a re-designed air intake and exhaust system that's paired with a new electronic control unit (ECU). The engine also received a boost in performance and thermal efficiency with an increased compression ratio that raised peak engine power by 8.5%. These changes allow for a cleaner, quieter and more powerful snowmobile capable of producing 38 kW of power. This snowmobile has a desirable MSRP of $10,420.69. These improvements result in a product that satisfies the goals of the SAE Clean Snowmobile Challenge, while still appealing to consumers.

Innovations

Analyzing the results from the 2018 SAE Clean Snowmobile Challenge, the University of Wisconsin team had areas to improve on.

The team focused on four main areas for improvement from the 2018 competition entry:

- Sound
- Performance
- New Independent ECU
- Emissions

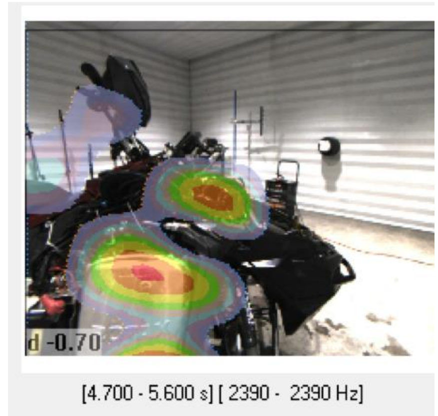
Research, development and testing in these areas led to innovation both in components and controls/calibration. The innovation section of this paper is divided into two primary sections: components and controls.

Components

Intake Noise Reduction

The two main sources of sound from a snowmobile are engine noise and track/chassis noise. This year the team focused on reducing the noise created by the engine. The team realized they could improve the intake design to alleviate one source of noise.

Intake noise at low loads is primarily caused by air pushing by the throttle valve and at high loads is primarily caused by the closing of the intake valves [2]. To combat this noise generation the intake was lengthened, and an air filter and sound box were added. The team tested in an anechoic chamber to quantify the sound reduction from the new design. The test was done with acoustic holography which used 30 independent microphones to pinpoint the area in which sound was being generated. With the microphones recording at a distance of 0.7 m away and the engine running at 5000 RPM the difference in noise generation by the two intakes was substantial. The test revealed the 2019 intake design reduced the intake sound from 88 dBA to 64 dBA. Figures 1 and 2 show the setup used during this testing and the results of the acoustic holography respectfully.



Figures 1, 2: Shows the setup used during the acoustic holography. Top image is with the 2018 intake and bottom image is the 2019 intake.

Exhaust Design

In 2014, the University of Wisconsin team discovered that the power output was not balanced between the cylinders. One cylinder produced more low-end power and torque. In an attempt to better balance the two cylinders by relieving a fraction of the back pressure it was decided to build a 2-into-2 exhaust system. This exhaust allowed for all EGR to be taken from cylinder one, which was measured to be the weak cylinder. Drawing all EGR from this cylinder reduces the load and allows it to draw more charge. Figure 3 shows the pressure traces recorded in the cylinders before balancing. The team did not have the time to gather empirical data to verify the cylinder pressures were balanced but did see a raise in manifold pressures at emissions mode 3 from 70 kPA to 80 kPa. In addition, studies conducted on reducing EGR back pressure have shown an increase in pumping efficiency [10].

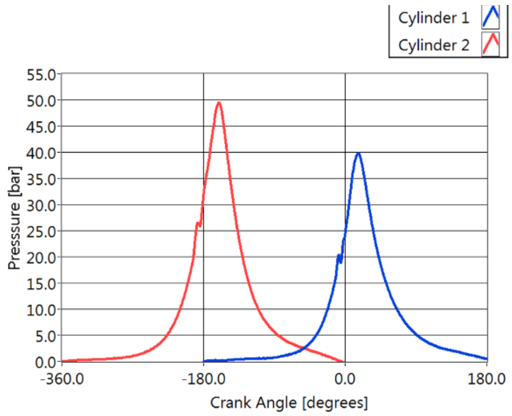


Figure 3: Shows the imbalance in peak pressure between the cylinders

Another benefit of the 2-into-2 exhaust design was the improvement in space utilization. The independent headers made it possible to use two catalytic converters. Using two catalysts improved the overall reaction volume from 1,117 cm3 to 1,307 cm3. The benefits of this catalytic converter volume increase is shown in more detail in the emissions section of this paper.

Heated Injectors

When doing research on how to improve cold start reliability last year, the Wisconsin team found information on heated injectors manufactured by Delphi as seen below in Figure 4.

Figure 4: HICM Heated Injector Control Module, developed by Delphi, along with heated fuel injectors.

The Delphi heated injectors were incorporated in Brazil where pure alcohol fuels are more commonly used. The team looked into integrating these injectors which would more effectively vaporize fuel and improve cold start reliability. The increased vaporization is due to an increase in surface area/volume of fuel due to the heat input. Issues were encountered during the implementation of the injectors, but a chance still remains to have them implemented by competition.

Increased Compression Ratio

Since the Wisconsin team bored and stroked the 600 ACE to 674 cc, they have run a stock 11.97:1 compression ratio. It is known that raising the compression ratio of a spark-ignited engine raises the thermal efficiency of an engine [1,2]. For the 2019 competition the team decided it could improve performance by raising the compression ratio of their engine to 13.14:1. This compression ratio was decided upon as it was the minimum head gasket thickness that maintained necessary valve clearance. A custom produced composite fiber head gasket made to the team’s specifications was acquired from Cometic.

The increase in compression required the team to re-calibrate the spark advance map to account for the change in cylinder turbulence and the shift in knock limit. The methods used in engine calibration are discussed later in the section discussing controls and calibration. The increase in compression ratio improved peak engine power output from 35kW to 38kW at WOT, which can be seen in figure 5.

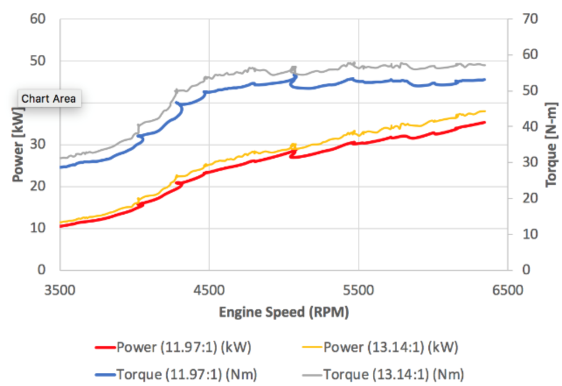


Figure 5: Experimental dynamometer torque and power curves comparing the new and old compression ratios

Controls

Integration of the PCM112

For the 2019 competition the team made the switch from the Motorola PCM565 128 pin controller to the Mototron 112-17 controller. This was a time-consuming undertaking involving a complete overhaul of the software, the design of a converter harness and weeks of troubleshooting. Switching to this controller allowed for a more concise wiring harness, and for better support from one of our most dedicated sponsors, Mercury Marine. The PCM112 is also significantly smaller than the PCM565. This compact build lead to major space savings in the area where the ECU was mounted, which both leaves room for other additions and makes maintenance easier.

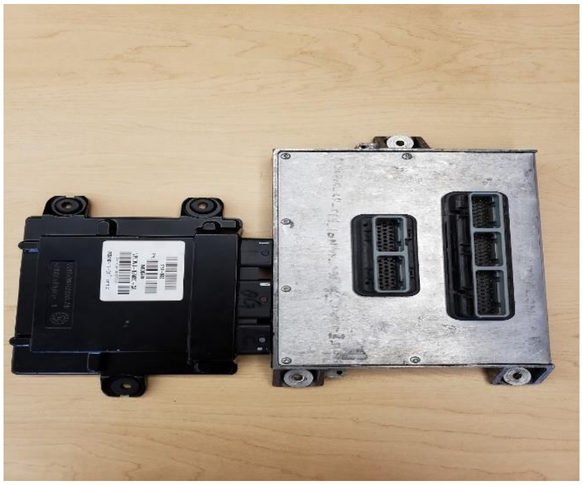


Figure 6: Shows the PCM112 and PCM565 difference in size and packaging.

Software Update

The first step in implementing the new controller was updating the software to work with said controller. The software target Operating System (OS) and controller target had to be updated to reflect the hardware of the new ECU. This change in controller target required redefining all input and output definitions in the software. Inputs and outputs were chosen in a way that the signal conditioning would most closely match the old ECU to limit the calibration work necessary during troubleshooting. Additional software changes were required during troubleshooting and are further discussed in the software section of the paper.

Hardware Update

The next step in the transition was designing and building a PCM112 harness. Since the team plans to use a new chassis next year, it was decided to utilize a converter harness instead of building a new harness for only one competition. Mercury Marine helped the team in a major way by building the harness to the specifications created by the team. This allowed the team to use the old wiring harness for operation and troubleshooting. In turn, this expedited the hardware process and allowed the team to begin testing the new software at an earlier date.

The 112-pin controller lacked one necessary digital frequency input which required the use of a frequency to voltage converter. When selecting this converter, the robustness of the hardware was the number one criteria. The Red Lion Controls IFMA0035, pictured in Figure 7, was chosen for its durable build and configurable signal conditioning.

Figure 7: Red Lion Controls IFMA0035 frequency to voltage converter.

Troubleshooting

The first issue the team found when testing the new software was the complete lack of signal from all digital inputs. A conductivity check from the sensors to the controller pins was completed to make sure all of the hardware was correct. External pullup resistors were then used in an attempt to acquire a signal on the controller. This additional hardware proved to be necessary as the controller read the proper signal after the addition and verified to the team something was missing in the software. After further inspection it was discovered the new controller required software to force the use of its pull up resistors on the digital inputs. An additional block was built in the code that was not necessary on the old controller as all of its resistors were wired without the option of not using them. Once the block was added to the simulink model the digital inputs began working properly without the external pullup resistors.

The next issue the team discovered was the lack of spark when trying to fire. The coil harness was conductivity tested and found to be correct. After further inspection it was determined the new controller was not compatible with the 5 pin “smart” coils that were previously being used because the new ECU has an internal power transistor unit. The team updated to 3 pin “dumb” spark coils to rectify this issue.

Once the new spark coils were installed the engine started and ran for the first time using the new controller. After a short period of running it was noticed the catalysts were firing at idle which is abnormal. Header temperatures were measured and showed the engine was only firing on one cylinder. Using a timing gun it was found only one coil was firing. Due to limitations in how the ECU OS handles encoder angle it was necessary to limit the injector and coil vector inputs to only read the first four elements of each vector. Figure 8 shows the simulink model of the new coil control software.

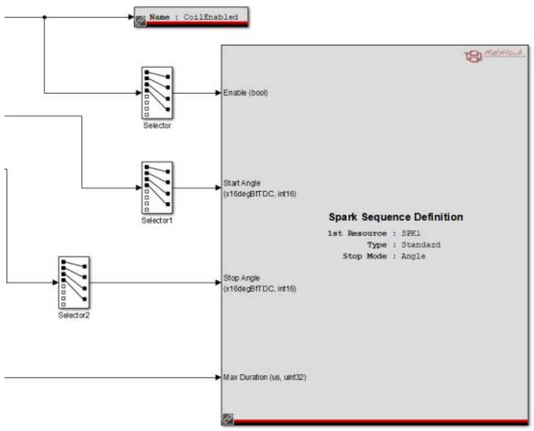


Figure 8: New Simulink model for coil control.

After this software update both coils were verified to be firing. The engine was started again and was found to still be running on one cylinder. To further investigate this issue, the crankshaft was marked at TDC for both cylinders and a timing light was used to see when each coil was firing during crank. Both coils were found to be firing when cylinder one was at TDC. The Rotax ACE engine has a 180-degree mechanical offset, so cylinder two was sparking at BDC.

To correct this issue, it was necessary to update the encoder definition which tells the coils how many degrees of crank angle after cylinder one TDC to spark. Because the controller was designed for use in larger engines, the encoder definition block had to be manipulated in a way that would provide the 180-degree offset between cylinders 1 and 2 without faulting. After working with Mercury Marine, the proper encoder definition was eventually found that allowed for both cylinders to spark at TDC.

Once the engine was running on two cylinders, certain actuators were found to be causing issues. One such issue was the engine had a difficult time maintaining speed at idle. Data logs were taken which showed the PID control on the EGR valve position was far too aggressive. This was likely caused by the change in hardware between the two controllers. The PID control was tuned and Figure 9 displays the results. It can be seen the valve maintains +/- 3% position.

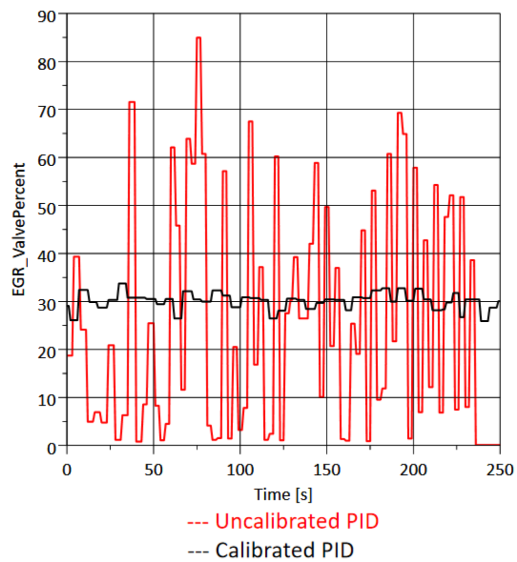


Figure 9: EGR valve % open before and after PID was tuned.

Team Organization and Time Management

The University of Wisconsin-Madison joined SAE in 1939. The Clean Snowmobile Team formed in the spring of 2001 and competed for the first time in Yellowstone in 2002 under the advisory and mentorship of Glenn R. Bower and eventually Ethan K. Brodsky, who started as a student and participant at the competition. The team has competed in the Internal Combustion class at the Clean Snowmobile Challenge since its formation and the Zero Emission class from 2008-2011. The Wisconsin team is led by Matt Massman in collaboration with Blake Bomkamp and Brandon Riehle. Through these multi-disciplinary student leaders, the team was able to tackle challenges in the material, mechanical, and chemical fields. With the rest of the team, various projects were accomplished in the calibration and electrical fields. Some major projects and their timelines are shown in the Gantt chart in the Appendix.

Outside of working on the snowmobile, the University of Wisconsin team organizes and participates in a number of fundraising, team building and community events. Every year the University of Wisconsin SAE organization participates in the SAE Milwaukee Chapter meetings to present their designs and accomplishments. The team is also awarded donations from the SAE during the event. Furthermore, the team annually presents the previous year's results to a major team sponsor: The United Wisconsin Grain Producers. The team also gave tours to other major sponsors, like Magna, Milwaukee Tool, Snap-On Tool, Mercury Marine, Fiat-Chrysler, Oshkosh Corporation and Ford Motor Company.

In a community outreach event before a Wisconsin Badgers' football game, the team encouraged and educated the use of biofuels to the public. The team interacted with the student body and community through various University of Wisconsin wide and College of Engineering specific events. At the beginning of the fall semester, new members are recruited through Engineering Bash, the College of Engineering's organization fair. Also, the Engineering Expo is held on campus, where the snowmobile is displayed to the public. It is a great opportunity for children to learn about snowmobiles and internal combustion engines. Other public events that the entire SAE organization displays team vehicles is at the Homecoming Parade and Badger Bash. Finally, various team events are organized outside of the shop to give opportunities for team bonding.

The team fell on some hard times at the beginning of January. After an accidental fire occurred in the shop area all of the University of Wisconsin SAE teams lost access to the shop that their vehicles are built in. Due to an ensuing safety review of the shop the team lost precious time in January and early February. They were able to overcome these hardships and managed to complete the design and build of their snowmobile.

Current Snowmobile Build

- Chassis: BRP, Ski-doo MXZ Sport, 2015
- Engine: Rotax ACE 600 (Bored and Stroked to 674 cc) 4-stroke, gasoline, 51 hp (experimentally recorded on water brake Dynamometer)
- Track: Camso Ripsaw II
- Muffler: OEM (Rotax)
- Catalytic Converter: Emitec Continental
- Skis: OEM
- Exhaust Gas Recirculation Valve: Delphi EG10176
- Exhaust Gas Recirculation Cooler: Custom Fabricated
- Injectors: Bosch EV-14-KT
- Battery: OEM
- Electronic Control Unit: Mototron PCM112-17 using Woodward Operating System

Engine Selection

The engine of the snowmobile is the most important factor in how the vehicle will perform in terms of sound and emissions, and this component was rigorously debated. The team weighed options in the two-stroke and four-stroke engine sectors.

Engine Option Evaluation

It is common knowledge that two-stroke power plants create more power in a lighter package than a common four-stroke engine. On the flipside, they produce far more emissions. On average, two-strokes emit double the CO and up to ten times as much HC compared to a four-stroke engine [3]. In addition to the three pollutants measured for competition scoring, direct injection two-stroke spark ignition engines are known emitters of 1,3-butadiene, benzene, and gas/particle-phase polycyclic aromatic hydrocarbons; all of which are classified as known or probable carcinogens by the U.S. Environmental Protection Agency (EPA) [4].

Final Selection

While a two-stroke engine could provide a lighter and more powerful machine, the team opted to go with a four-stroke because the emission score goal the team set would be unattainable with a two-stroke. Table 1 compares the four-stroke options available from manufacturers and also includes one of the cleanest two-stroke engines for contrast. The team focused on power, fuel economy and weight of each engine to assist in making the final decision.

Table 1: Engine Comparison of Leading 4-Stroke Snowmobiles [3]

Base Engine	**Power (kW)**	**Weight (kg)**	**Fuel Economy (km/L)**	**Emissions (g/kW-hr)**		
				HC	**CO**	**NO_x**
Ski Doo ACE 600	42[1]	41.1	12.5	6	90	N/A
Ski Doo ACE 900	64.5 [2]	51.8	10[3]	6	75	N/A
Ski Doo 1200 4-TEC	92	60	8.85	8	130	N/A
[4]Polaris 600 Cleanfire	97	35	5.3	60	175	N/A

[1]*OEM Reported Power*
[2]*Sport mode operation*
[3]*Eco mode operation*
[4]*Two-Stroke for comparison*

Each engine in the table meets current EPA regulations, but only the ACE 600 and 900 options excelled in the emissions and fuel consumption category [3]. The ACE design utilizes integrated engine lubricant and cooling systems, which reduces external plumbing, reduces weight and is overall simpler. These innovations made alteration and implementation of Wisconsin's design changes much easier. Table 2 analyzes the 600 and 900 ACE options in greater detail.

Table 2: Specifications of the Rotax ACE 600 and 900 engines

	ACE 600	ACE 900
Engine Type	Four-Stroke	Four-Stroke
Cooling	Liquid	Liquid
Cylinders	2	3
Displacement (cc)	600	900
Bore x Stroke (mm)	74 x 69.7	74 x 69.7
Ignition	Bosch	Bosch
Exhaust	2 into 2	3 into 1
Fueling	Electronic PFI	Electronic PFI
Compression Ratio	12:1	12:1

Aside from power, the ACE 600 outperformed the 900 option in fuel consumption, emissions quality, cost and weight. With this many advantages, the ACE 600 was the clear choice for the Wisconsin Team.

Engine Simulation and Optimization

Using Ricardo Wave, the team built a 1-dimensional engine model to assist in improving power output and driver friendliness of a 600 ACE. The three main techniques to increase power of an engine are: raising cylinder pressure, running at higher engine speeds, and increasing engine size [2]. To increase cylinder pressure, it is possible to simply introduce a turbocharger or supercharger to the system. Some drawbacks to this option however is the increased complexity and weight, as well as potential to lose efficiency. Increasing engine speed would increase power, at the cost of efficiency loss due to increased friction. This option would also require a re-design of transmission and clutching systems on the snowmobile. This left the team with the choice to alter the dimensions of the ACE 600 engine. Increasing the displacement of the 600 ACE gives the team extra power, but still utilizes the cheaper and lighter frame rather than just going to the 900 ACE package.

The team used the 1-dimensional engine model to quickly optimize the dimensions of the power plant. The stock bore and stroke of the 600 ACE is 74 mm by 69.7 mm. Sweeps were conducted from 69.7 mm to 75.7 mm (the maximum stroke possible using the stock crankcase). The bore value was also swept from 74 mm to 76 mm. The team settled on using a new displacement of 674 cc, with a bore and stroke of 75 mm by 75.7 mm. This setup increased power and peak torque by 8.2% and 7.3%, respectively. Figure 10 shows the change in simulated power output at 5000 rpm, peaking at 32.5 kW.

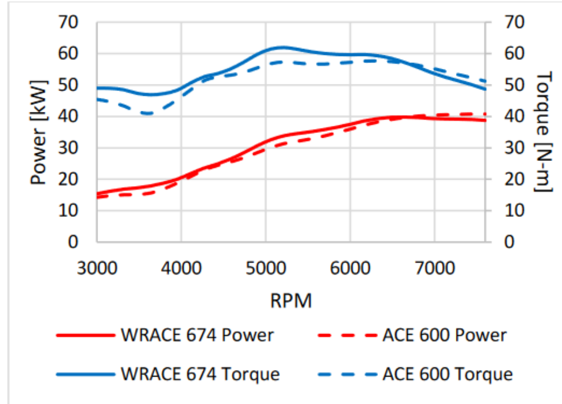


Figure 10: Torque and power curves for the stock ACE 600 and optimized WRACE 674 engines simulated with a Ricardo Wave model

To confirm the simulated data, the team ran power sweeps with the 2019 water brake dynamometer setup. Figure 5 shows the data confirming the Ricardo Wave model predicted 38 kW peak power and 58 Nm peak torque.

Because the bore and stroke were changed, the team also needed to examine whether or not to adjust the timing of the intake and exhaust camshafts. The team swept intake timing by 5 degrees advanced and 5 degrees retarded from the stock timing. These changes made little difference in the torque at each timing, so the team concluded the stock intake and exhaust camshafts would suffice for our application.

Powertrain Enhancement

The stock Rotax ACE 600 is a highly efficient engine featuring diamond-like carbon coatings on the surface of the tappets and a magnesium valve cover [6]. With this engine the Wisconsin team was still able to find areas to be improved. Such areas include but are not limited to the efficiency, fuel economy, and power.

Boring and Stroking

An analysis indicated that the a ‘square’ (stroke = bore) engine provides improved fuel efficiency and more low-end torque for trail riding applications. The Wisconsin team then took this information and put it to use. First, the stroke was limited by the clearance in the stock block including a windage tray in the casting. With this limitation a new stroke limit was able to be obtained from machining a Honda CBR954RR piston to get a stroke length of 75.7 mm. With this set, analysis moved on to bore dimensions.

The Wisconsin team chose to go with a forged piston made from 2618 T6 high tensile aluminum because of their superior mechanical properties over cast pistons. With the desired new specifications required for the piston to fit Wisconsin’s new bored and stroked engine included a higher wrist pin location and a shorter skirt to ensure the piston would be confined to the original bore of the engine. It was determined a 75mm piston designed for a Honda CBR954RR motorcycle and made by Wiseco, met almost all of Wisconsin's criteria while allowing for the utilization of stock connecting rods.

The new pistons had a different geometrical design compared to the stock ACE piston. Things that need to be addressed were the V-shaped high compression ratio dome on the stock Honda CBR954RR piston, and the wrist pin offset being in the wrong direction. The face was modified to ensure proper valve clearance and combustion chamber geometry. Additionally, the wrist pin needed to be modified so the exhaust reliefs were machined to fit the intake valves and the pistons were reversed. The Wisconsin team machined the pistons in-house to create a two-tiered bowl design shown in Figure 11 mimicking the stock ACE piston. The final dimensions of the modified piston compared to the stock piston are shown in Table 3.

Figure 11: Pictured from left to right: stock Rotax piston, unmodified Honda piston, and machined Honda piston with two tier piston bowl design to improve mixing in combustion chamber

The Wisconsin team looked at the stock 600 engine manual to achieve the appropriate bore diameter. From this the Wisconsin team provided a calculated bore diameter specification of 75.3 mm, which provided a 'medium' clearance. This information was then given to an advanced engine machinist who then bored the cylinder walls.

Table 3: Table comparing the stock Rotax ACE piston to the modified Honda Piston from Wiseco

	Rotax Stock	**Honda Modified**
Diameter (mm)	74	75
Wrist Pin Diameter (mm)	17	17
Wrist Pin Location (mm), (relative to compression ring)	28	25.5
Compression Ring to Deck Height (mm)	5.5	5.12
Mass* (g)	254.5	219.36
Bowl Size (cc)	5	5.15
Skirt Length from bottom of Wrist Pin (mm)	9.6	6.4

**Mass includes piston, rings, wrist pins, and clips.*

Ported Head

To compensate for having a larger displacement engine, the team looked for ways to increase airflow. The option the Wisconsin Team chose was hand-porting the heads of the engine. Porting removes the bottom material of the ports where the highest velocity and most dense air flows during intake and exhaust strokes, allowing for more air to enter the combustion chamber. The team used a calibrated flow bench to measure the air flow into the intake and exhaust across the valve lift profiles. The exhaust valves saw a large improvement from porting; a 5% to 7% increase in flow across the entire valve lift (Figure 12).

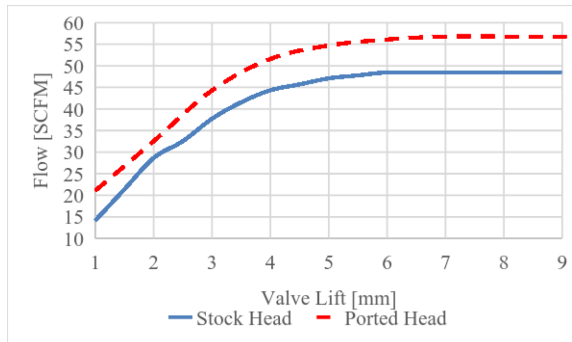


Figure 12: The exhaust ports of the ported head compared to the stock head. The ported head shows flow improvement across the valve lift profile

Calibration and Control

The WRACE 674 currently uses the stock 600 ACE Electronic Throttle Body (ETB) in combination with a mass airflow (MAF) sensor, manifold absolute pressure (MAP) sensor, and dual NO_x/O_2 sensors, relayed directly to the Mototron ECU. These sensors combined with various actuators enable the team to calibrate and control fuel injection and develop a fuel control strategy. Many hours were spent by team members both in past years and leading up to the 2019 competition calibrating the control system and ETB PID controller to optimize it for idle, startup and drive.

Typically, when calibrating an engine, the main goals are to minimize Brake Specific Fuel Consumption (BSFC) under part-throttle operation and to maximize torque at Wide Open Throttle (WOT) while staying within specified constraints. Typical constraints consist of emissions levels, running quality, exhaust gas temperature limits, knock limits, and engine speed [7]. These constraints define a window, shown in Figure 13, that the engine must be calibrated to operate within.

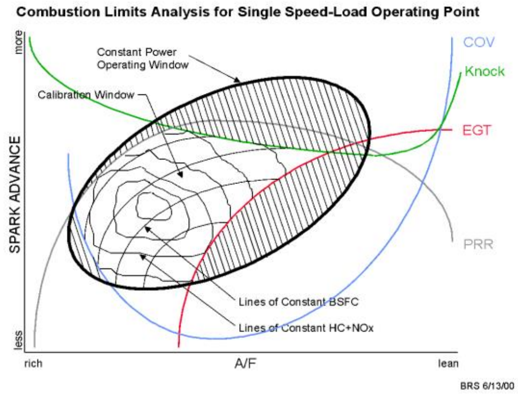


Figure 13: Graph of typical calibration window [2]

Calibration of the 2019 engine shown in Figure 14 was performed using a Land & Sea water-brake dynamometer, wideband oxygen sensors, and exhaust thermocouple probes in conjunction with Optrand spark plug pressure transducers and ¼ degree resolution shaft encoder. By monitoring torque, exhaust temperatures, peak cylinder pressure, fuel flow, and AFR values, spark timing and fueling were properly calibrated. Utilizing a pressure trace, as shown in Figure 15, in conjunction with fuel flow measurements, spark advance was precisely calibrated to ensure low BSFC, high heat release rate, Maximum Brake Torque (MBT), and low tailpipe emissions.

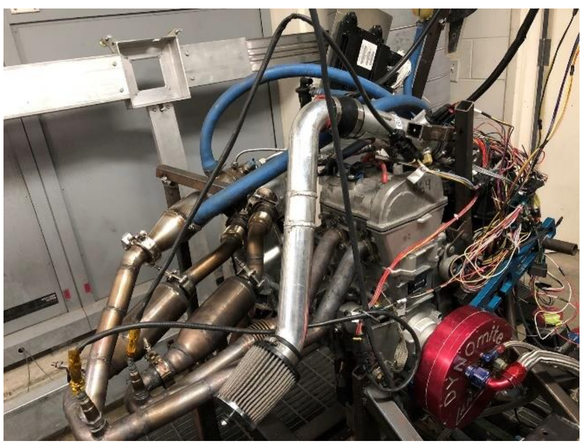


Figure 14: Dynamometer testing stand used for calibrations

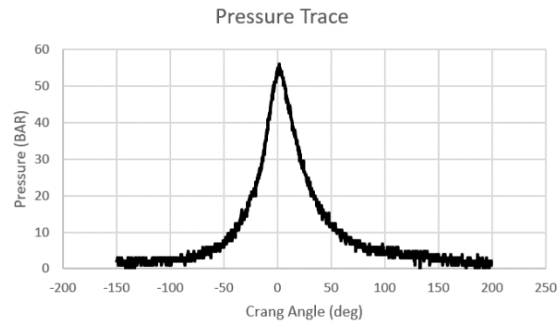


Figure 15: In-cylinder pressure trace taken at lab emissions mode 3

EGR Startup Delay

Data logs from cold starts presented another interesting issue with the snowmobile. Occasionally after sitting outside overnight and then cold starting, the engine speed would drop by almost 800 RPM while idling. This phenomenon happened roughly 100 seconds after starting, and after analyzing multiple data logs, the root cause of the issue was found. The EGR valve was set to a 10 second delay on startup, but after this time passed and EGR was enabled, the valve would not open to its desired idle setpoint. After the engine coolant temperature (ECT) reached a certain level, usually around 30°C to 40°C, the valve position would then overshoot its setpoint by over 160% before settling back in, as can be seen in Figure 16.

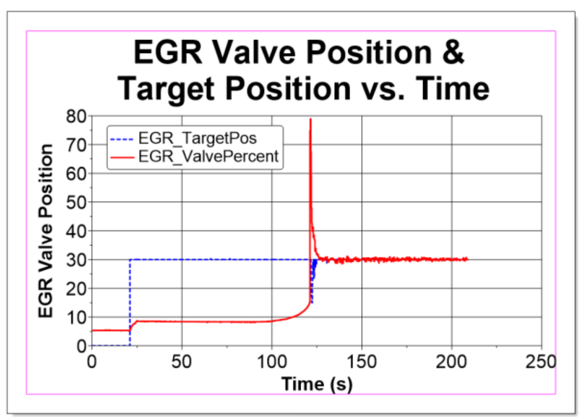


Figure 16: EGR Valve Position and Target Position while idling after a cold start

Using data analysis and engineering judgment, it was deduced that condensation in the exhaust was freezing the valve in place overnight, and the EGR Valve PID controller was reaching its maximum output to drive the valve to its desired setpoint. More specifically, this phenomenon was a case of I-term windup caused by a mismatch between the idealized model and the non-ideal behavior of the system after being kept outside overnight. Once the engine reached a high enough temperature for the valve to break free, the controller drove the valve to overshoot before bringing it back to the setpoint. To eliminate this issue, an ECT based

EGR valve delay was created in the engine code as shown below in Figure 17. This delay was then calibrated to a desired ECT allowing the valve to thaw before attempting to open it.

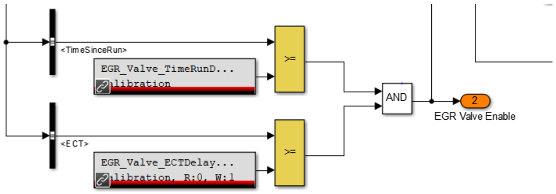


Figure 17: New branch of Simulink engine code containing ECT based EGR valve delay

Exhaust Gas Recirculation

The Wisconsin team chose to implement an exhaust gas recirculation (EGR) system to further minimize nitrogen oxides (NO_x), by returning a fraction of the exhaust gas back into the intake system. NO_x is formed at high combustion temperatures by the dissociation of oxygen and nitrogen found in the air inducted into the cylinder. The recirculated exhaust gas is mixed with fresh air and acts as a diluent, reducing the peak burned gas temperatures and NO_x formation respectively [2]. Studies have shown cooling the exhaust gas before introduction into the intake can further reduce emissions and improve fuel economy in high speed applications, as well as reduce the production of in-cylinder CO [8,9]. For these reasons, the team also designed an optimized 16 "rough" surface inner-tube EGR cooler for further emission reduction, shown in figure 18. The cooler was paired with a Delphi EG10176 EGR valve. Flow bench testing was done which showed the valve was capable of providing 16.1 kg/h of EGR. Under normal operating temperatures this system was able to provide exhaust gas at a consistent temperature of 55 °C.

Figure 18: The sixteen tubes of the cooler were spaced to maximize the amount of turbulence in the cooler resulting in the highest amount of heat transfer out to the engine coolant

NOx Reduction

The Ricardo Wave model used earlier can also be used to assist in designing our EGR system. To get an idea of what our system was capable of, the Ricardo model was used across a range of RPM's and EGR percentages. To confirm the predictions made by the model, the team used a Continental Smart NO_x sensor to collect data through the five emission modes used at the CSC. The EGR valve duty cycle was adjusted at each mode point to determine the change in NO_x emissions. Figure 19 shows the effect from EGR, obtained during dynamometer testing.

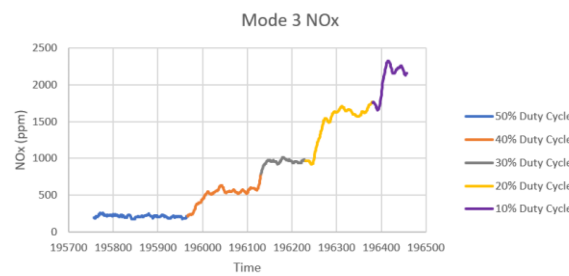


Figure 19: Recorded NO_x emissions in the team's estimated Mode 3 at various EGR percentages, recorded while running non-oxygenated 91 octane fuel

The NO_x emission data collected during calibration was used to select appropriate EGR valve duty cycles for testing. The goal during testing was to achieve peak NO_x reduction as well as maintain torque output. The results of these tests lead the team to Table 4.

Table 4: Shows EGR mass percentage of intake air calculated using stoichiometric fueling for E0 fuel

Mode	1	2	3	4	5
Mass % EGR of intake air	0%	5.5%	12.3%	16%	18.7%

Control Hardware

The Wisconsin team currently utilizes a Mototron PCM112-17 ECU embedded with a Simulink based Motohawk operating system designed by Woodward Inc. This controller has a total of 112 pins, including 23 analog inputs, 4 digital inputs, 15 low side driver power outputs, 16 logic level outputs and a triple CAN 2.0B interface. It is ideal for snowmobiles due to its durable nature, with the ability to withstand temperatures from -40°C to 85°C, vibrations up to 50G, and submersion in water up to a depth of 3 meters. In addition, the Motohawk software provided by Woodward auto-generates code from the Wisconsin Simulink model.

Fuel System Modifications

To run ethanol-based fuels, modifications were required for the fuel delivery system to maintain performance and emissions levels the team is targeting. To compensate for the lower heating value of ethanol, fuel injectors with a higher flow rate replaced the stock injectors. The specifications for the new injectors are given in Table 5.

Table 5: Fuel injector specifications

	Stock Injector	**WRACE Injector**
Manufacturer	Continental	Bosch
60 Sec Flow (g)	160	237
Spray Angle	20º	20º
Rail Pressure (kPa)	400	300

Because the injectors increase fuel flow, a larger fuel pump and fuel filter are also needed. The team selected a Walbro fuel pump capable of 255 L/hr. They also selected an inline 40-micron stainless steel fuel filter with a capacity of over 454 L/hr. This filter is reusable, and provides sufficient fuel flow the injectors, regulator, and flex fuel sensor.

To guarantee performance across all ranges of ethanol content from 0% to 85%, the team utilized an inline Continental Flex Fuel sensor. The sensor reports fuel conductivity and temperature and uses a dielectric measuring principle to detect the amount of ethanol in the fuel [8]. Since air-fuel ratios are calculated on a gravimetric basis and fuel injectors are measured on a volumetric basis, the fuel temperature is measured to allow for density compensation.

The controller is fed the fuel property information, along with the MAF sensor data. Instead of using correction tables for deviations from the base calibration, the Wisconsin team calibration provides a global AFR which is used to calculate the correct fuel injection based on the information from the flex fuel sensor and the MAF sensor.

Emissions

For the 2019 Clean Snowmobile Challenge, the Wisconsin team worked with Continental Emitec GmbH and W.C. Heraeus GmbH to implement a two-way catalyst to reduce HC, CO and NO_x. Platinum is the main oxidizer for HC and CO reactions, while Rhodium is used reduce NO_x.

To fully optimize the precious metal washcoat, exhaust gas was tested pre and post catalyst using a Snap-On five gas analyzer. This was done while recording fuel flow, mass airflow, equivalence ratio and exhaust gas temperatures. To quantify the catalyst data, catalytic efficiencies were calculated for the three major CSC emission sources, shown in Table 6.

Table 6: Showing the catalytic efficiencies averaged across the 5 CSC mode points. Catalysts 1 are the new catalysts for CSC 2019 and catalyst 2 is the catalyst used in CSC 2018. Catalytic efficiency = (precatalyst emittent - postcatalyst emittent)/precatalyst emittent*100%

	HC	**CO**	**NO_x**	**Projected E-Score**
Catalyst 1 Efficiency	99.9%	96.3%	33.9%	206.2
Catalyst 2 Efficiency	99.9%	92.4%	34.2%	205.9

* Low NO_x efficiency is assumed to be occuring due to a low concentration of NO_x entering the catalyst. This is due to the EGR NO_x mitigation.

Working with Heraeus, a platinum/rhodium-based washcoat was applied to Emitec's metal honeycomb substrate. The improved catalytic efficiencies are due to the increased volume of the catalytic converters. This along with the improved power output of the engine allowed for the team to improve on its already impressive E-score.

Table 7: 2019 CSC Wisconsin Catalysts' substrates and loading data

Manufacturer	W. C, Heraeus GmbH
Diameter (mm)	80
Length (mm)	130
Foil thickness (mm)	0.03
Substrate	Emitec Metal Honeycomb
Density (cpsi)	400
Loading (g/ft^3)	Platinum 25
	Rhodium 25

*This is for each of the catalysts, dual exhaust with one catalyst for each header

To optimize the alleviation of CO, HC and NO_x, the exhaust gases entering the catalysts must alternate between slightly rich and slightly lean [2]. When a lean exhaust mixture passes through the catalytic converter, excess NO_x is absorbed on the surface of the substrate while the CO and HC are oxidized to H_2O and CO_2 in the presence of excess oxygen. In contrast, when a fuel-rich exhaust mixture goes through the catalyst, the NO_x is released from the substrate and immediately reacts with the HC and CO to form N_2, CO_2 and H_2O [2].

The Wisconsin team applies a MAF-based fueling algorithm with a target equivalence table. From there, the closed loop fuel trim algorithm, which utilizes the heated wideband oxygen sensor, is activated and responsible for fine tuning the air-fuel ratio and lean-to-rich oscillation at a stoichiometric level. The computing power of the Mototron controller is used to continually optimize the correct fuel injection amount using the intake mass air flow rate, the fuel density and the desired fuel air ratio, shown in Figure 20.

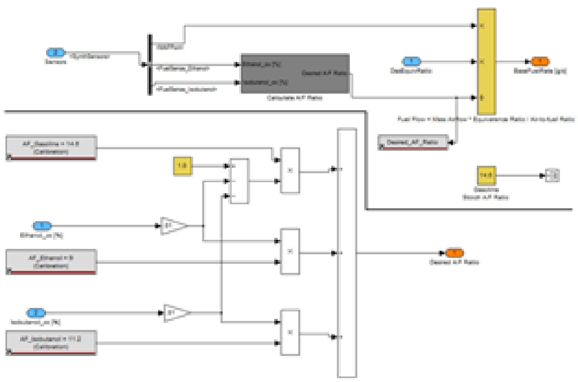


Figure 20: Simulink block diagram for flex-fuel and isobutanol engine control strategy

The combination of the optimized washcoat and the closed loop fuel algorithm with the wideband oxygen sensor provides an ultraclean snowmobile. The projected E-score for Wisconsin's 2019 CSC entry is experimentally estimated to be 206.2. Table 8 shows projected 2019 weighted 5-mode lab emissions results against stock ACE 600 emission results.

Table 8: Emissions of the stock ACE 600 and WRACE 674

	WRACE 674	**ACE 600 [5]**
CO (g/kW-hr)	6.0	90
HC (g/kW-hr)	0.006	8
NOx (g/kW-hr)	3.501	N/A
E-Score	206.2	190

Sound Reduction

Prior to the 2018 CSC the Wisconsin team made major improvements to the track/chassis noise of the WRACE 674. To reduce the noise generated through vibrations of the tunnel, the team applied a frequency damping product known as LizardSkin® which is shown in Figure 22. Testing was done with the damped and undamped tunnel hanging from the ceiling. The chassis was struck with a consistent force and accelerometer data was collected and sent to an oscilloscope. A Fast Fourier Transform (FFT) was applied in Matlab to convert the time based data to a frequency domain for data analysis.

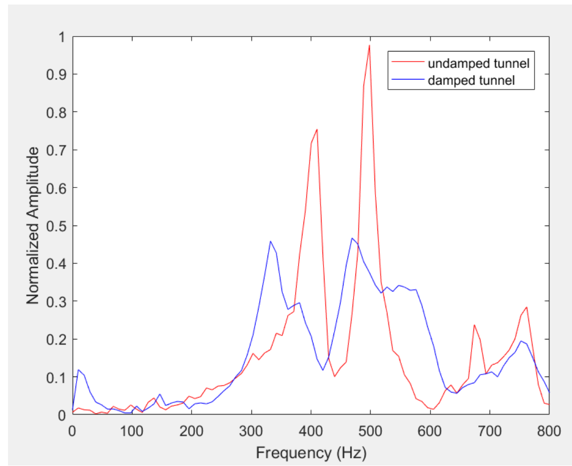


Figure 21: Normalized tunnel frequency amplitude comparison of damped and undamped 2015 chassis

Figure 21 shows the comparison between the 2015 chassis damped and undamped tunnels. The addition of dampening to the 2015 tunnel shifted the fundamental frequency from 400 Hz to 314 Hz and reduced the amplitude of the tunnel. The new fundamental frequency of the tunnel is about three times that of the engine which prevents resonating sound vibrations.

Figure 22: View of tunnel underside lined with Lizard Skin material

In sound testing using Extech 407736 microphones using an A-weighted decibel range with two microphones set up 15 meters from the tests runs the 2019 WRACE 674 came in at and average of 66.2 dBa compared to the 2018 WRACE 674 setup which came in at an average of 72.4 dBa.

Conclusions

The 2019 University of Wisconsin Clean Snowmobile Challenge entry improves upon previous Wisconsin Rotax ACE entries in sound and emissions performance. It fulfils CSC requirements while remaining desirable to the consumer. The WRACE 674 is a 674 cc four-stroke engine that has improved power output of 38 kW coupled with improved sound testing at 66.2 dBA and reduced brake specific emissions. The improvement on mechanical sound with previous implementation of chassis sound reduction techniques makes it the quietest entry the University of Wisconsin has obtained in years. The WRACE 674 features a new, improved electronic control unit with superior computing speeds. This package comes fully flex fuel capable of running E0 to E85 fuels. The WRACE 674 is cleaner, quieter and features improved performance while coming in at a desirable MSRP of $10,420.69.

References

[1] G. Nellis and S. Klein, *Heat Transfer*. Cambridge University Press, 2009.

[2] J. Heywood, *Internal Combustion Engine Fundamentals*. New York: McGraw Hill, 1988.

[3] “2015-Present Snowmobile Engine Certification Data,” United States Environmental Protection Agency, 2018. [Online] Available: https://www.epa.gov/sites/production/files/2018-01/snowmobile-2015-present.xlsx [Accessed 16 02 2019]

[4] "The Clean Air Act Amendments of 1990 List of Hazardous Air Pollutants," United States Environmental Protection Agency, 1990. [Online]. Available: http://www.epa.gov/ttn/atw/orig189.html [Accessed 15 02 2019].

[5] BRP-Ski-doo, " Engine Technologies-Rotax ACE 600.," [Online]. Available: https://www.rotax.com/en/products/rotax-powertrains/details/rotax-600-ace.html [Accessed 15 02 2019].

[6] M. Gumpesberger, S. Gruber, M. Simmer, C. Sulek and e. al., "The New Rotax ACE 600 Engine for Ski-Doo," SAE Technical Paper, pp. 2010-32-0001, 2010.

[7] B. R. Suhre, "Mototron Engine Control and Calibration Basics Rev. 10," Mototron Corporation., 2006.

[8] T. Alger, "Clean and Cool-Cooled EGR improves fuel economy and emissions in gasoline engines," 2010. [Online]. Available: https://www.yumpu.com/en/document/view/23177021/clean-and-cool-southwest-research-institute. [Accessed 17 02 2019].

[9] SAE International, "Cooled EGR shows benefits for gasoline engines," 17 September 2014. [Online]. Available: https://www.sae.org/news/2014/09/cooled-egr-shows-benefits-for-gasoline-engines. [Accessed 17 02 2019].

[10] SAE International, “The Effects of Intake Pressure on High EGR Low Temperature Diesel Engine Combustion,” 25 October 2010. [Online]. Available: https://saemobilus.sae.org/content/2010-01-2145. [Accessed 17 02 2019]

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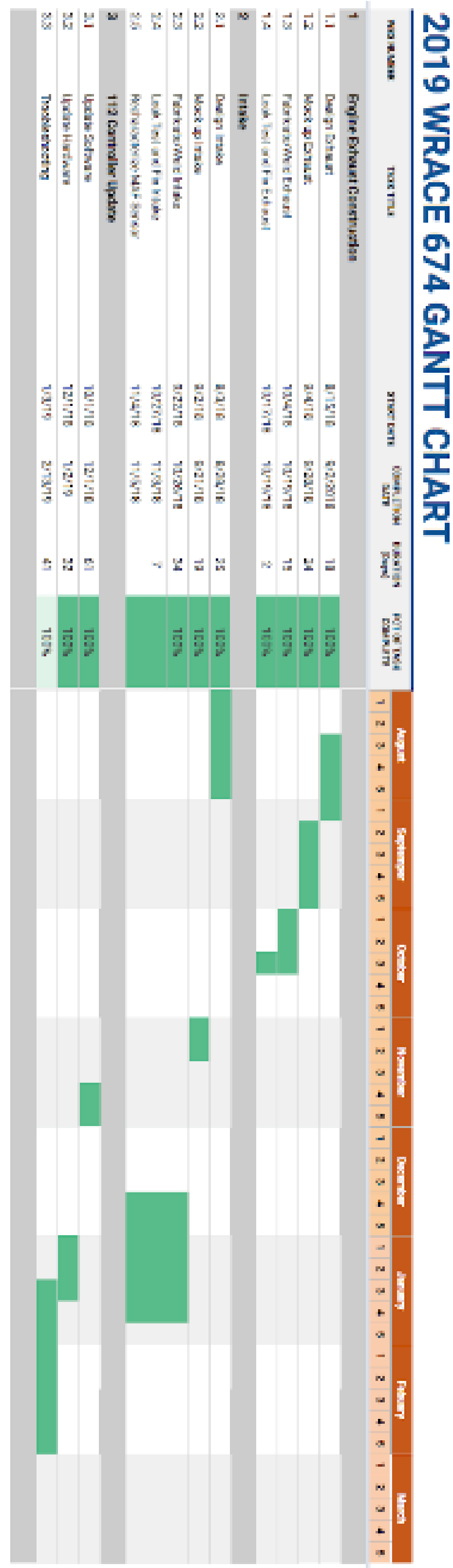
Appendix



Definitions/Abbreviations

AFR	Air/Fuel Ratio
ACE	Advanced Combustion Efficiency
BAT	Best Available Technology
BSFC	Brake Specific Fuel Consumption
CAN	Controller Area Network
CO	Carbon Monoxides
cpsi	cells per square inch
CSC	Clean Snowmobile Challenge
ECU	Electronic Control Unit
EES	Engineering Equation Solver
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
ETB	Electronic Throttle Body
FFT	Fast Fourier Transform
HC	Hydrocarbons
MAF	Mass Air Flow
MAP	Mass Air Pressure
MBT	Maximum Brake Torque
MSRP	Manufacturer Suggested Retail Price
NO_x	Nitric Oxides
OEM	Original Equipment Manufacturer
OS	Operating System
PID	Proportional Integral Derivative
RPM	Revolutions per Minute
SAE	Society of Automotive Engineers
WOT	Wide Open Throttle
WRACE	Wisconsin Rotax Advanced Combustion Efficiency